

High-Resolution Continuum Observations of the Sun

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When I first came to this city in 1954 the focus of the new wave in solar physics was on the study of the chromosphere and corona. While astronomers of the Unsold school were still pursuing the problems of limb darkening and models of the photosphere, the exciting problems seemed to be in the tenuous atmosphere where so many remarkable phenomena occur. One reason, at least for me, for the lack of interest was the small scale of photospheric fine structure. The mean free path of radiation and particles is short, and the structures were below the level at which we could study them with the resources then available. Today the situation has changed. The Lockheed results from Spacelab have shown how much complex and interesting structure there is in the photosphere. Our videomagnetograph movies have revealed the fascinating details of magnetic field evolution in the photosphere. And the development of helioseismology has brought renewed interest to the subsurface region.

Another reason the photosphere was neglected is that the phenomena seemed quite straightforward. But the discovery of exploding granules at Pic du Midi showed that there were unexpected hydrodynamic phenomena present, and the Spacelab observations have shown how this structural phenomenon affects the velocity and brightness pattern of the photosphere.

It is important for the HRSO project to learn as much as we can about the solar granulation in different wavelengths. Of course a major step forward has been made in the Spacelab observations. But since Spacelab cannot fly very often and the wavelength range and other factors are limited, it behooves us to do the best we can from the ground. At Big Bear we have done this by videotape recording of the granulation image. This makes it possible to take many frames and pick out the best ones. The movie that I will show you was made by some Caltech students this summer, Haimin Wang, Matt Penn, and Mark Looper, as well as Bill Marquette of our observing staff. From each videotape the best image in a 10 second range was chosen and digitized with our image processor. The image processor was then used to register the frame with the time zero frame. In this way a movie lasting about an hour was produced; however there is a 15 minute break in the middle. I believe this technique gives us a powerful way to reconnoiter the range of HRSO; it can be applied to all solar observations where video may be used. Although it does not improve individual frames, it makes possible evolutionary studies with sustained high resolution. Further improvement will include smoothing with various algorithms and summing of frames. Unfortunately it cannot be applied to videomagnetograms, where we already are summing.

The evidence from our granulation film is most interesting. We find that the typical granular lifetime is about 15 minutes. Why is this so much longer than the canonical value of 8 minutes? Because it takes 8 minutes for the granule to form and 8 minutes for it to explode or fade. We quickly see the importance of the "explosion" phenomenon

on granular structures. And we begin to see how sunspots form. We already have other, better videotapes which will be processed this winter, and we expect to explore the other aspects of this work, in particular the variation of granule appearance in other wavelengths and near the limb, as well as the behavior in strong magnetic fields.

The aim of the PFI or photometric filtergraph instrument is to observe the sun in the continuum with as high resolution as possible and utilizing the widest range of wavelengths. In the original proposal we combined the high resolution and high data accuracy of film with the high photometric capacity and wavelength range of a CCD. Those observations were to cover the range from 1100 to 7000Å. Because of financial and political problems the CCD has been eliminated so that the highest photometric accuracy is only obtainable by comparison with the CFS images; furthermore we are presently limited to wavelengths above 2200Å due to the lack of sensitivity of untreated film below 2200Å. Therefore the experiment at present consists of a film camera with 1000 feet of film (16000 exposures) and 12 filters. To picture what can be accomplished with even that limited instrument, one should consider what the Lockheed Spacelab data would look like with HRSO resolution, twelve wavelengths and many targets.

It is commonly thought that HRSO has no ultraviolet capability. That statement is wrong, unless the ultraviolet range has been redefined. The PFI reaches to 2200Å and can go further if someone will find money for it. We expect to do significant science in that region.

Why is it valuable to observe the continuum? First, continuum is easy to understand, or at least easier than lines which suffer from non-LTE effects and can be hard to interpret. Second, Lyot filters are not very effective in the blue, so a wider spectral range is available, particularly the UV. Third, the short exposures and lack of possible image degradation by the Lyot filter appear to permit higher resolution observations in the continuum. Our observations of continuum features suggest that the features low in the atmosphere that are observed are smaller than those observed higher up in the Lines. Broad-band filter observations will outline elements of the magnetic field rather well. Finally, the potential resolution of the telescope is doubled in the near UV, a fact of increased importance as we face utilization of a 1 meter aperture. This makes the mirror figure of critical importance; with a proper mirror we can resolve 0.07 arc sec at 2200Å.

The Lockheed results from Spacelab have shown how much one can learn from even a brief sequence of continuum images. Although the granulation appears relatively featureless superficially, high resolution observations show it full of the most remarkable structure; and that structure is fundamental to an understanding of the photosphere.

Unfortunately granulation studies can only occur from the ground over very brief intervals and are quite limited in what they can tell us. Our knowledge of the dependence of granular contrast on wavelength or on distance from sun center is sketchy at best. Although the removal of the CCD makes it difficult for us to carry out the best photometry, the steadiness of the HRSO images should make it possible for us to determine at least relative contrast to a reasonable degree of accuracy. Some calibration information will come from comparison with the CFS. Furthermore, steady images of the same field will allow us to carry out measurements of the oscillatory component which will enable us to extend the power versus frequency diagram of the 5 minute oscillation to still higher

values. One advantage of film is that it covers a large field with high resolution. This will enable us to obtain a relatively large sample of granulation with a relatively small number of sequences.

Observation with filters in the blue clearly reveals the network magnetic elements. We have found this works best with a 10 Angstrom filter centered on the K-line, but we may also see it with a filter at 2000\AA , for example. We expect that with the resolution of HRSO the contrast of such images should be even better. The appearance of the granulation in the blue is quite different from that in the visible, partly because of the many lines and partly because we are looking at a different height. We hope for the first time to quantify this difference. As I mentioned, we can easily see the small elements of magnetic flux on the surface, where the chromospheric heating is taking place. By combining the highest resolution granulation and magnetic observations with one instrument, we should be able to say more about the detailed relation of granulation changes to magnetic field changes. Only the strongest intranetwork magnetic elements are presently visible with the broadband K-line filter, so we will have to rely on the CFS magnetograms to determine the correlation between granular motion and the intranetwork fields. The evidence is that the intranetwork field generation brings about 100 times more flux to the surface of the sun than the ephemeral regions which in turn bring more than 100 times more flux to the surface than the sunspots. I would guess that the intranetwork fields are generated by granular motion, but we cannot tell without detailed observation.

The PFI experiments are outlined in Fig. 1 and Fig. 2. These experiments were developed when we had two cameras. Reduction of our experiment means we will have to cut out some of these; we are facing those decisions now. I discuss some of the problems we will address:

Surface Flows

As soon as one has mileposts one can look for surface flows. In the weak magnetic fields we can detect flows on the order of 0.1 kilometers per second. The granulation lifetimes are unfortunately limited, but there is a certain continuity in the pattern that may make it possible for us to follow granular structures for longer than that. Of course, small pores and sunspots will be even better for this purpose. We will search for flows, with the particular goals of looking for velocity field and supergranular cells, the moving magnetic elements near sunspots, and other features. A particularly striking example of this fluctuation are the very small points which one observe to oscillate in the K-line and in the blue. The relationship of these points to the magnetic field is not clear.

Magnetic Fields

Besides the questions of the interaction of magnetic fields with granulation and other flows, one of the most important problems that HRSO will address will be the size of the magnetic field elements. Stenflo and others have presented arguments that the elements of flux must be quite strong, of the order of 1000 Gauss. To match the measurements of total flux in the magnetic elements we see, this means that they must be of the order of

50 kilometers across, approximately .07 arcseconds. There is no better way to resolve this question than to look at the elements and see what is the best thing we can resolve. Now so far as we know most of the magnetic elements in the low chromosphere/upper photosphere reveal their presence by local brightening. These are observed as bright points in the continuum, particularly on the edges of the network. In a recent study, we found that the contrast of these elements increases to the limb, but the maximum contrast of a 1 arcsecond magnetic element is about 30%. It is a curious contradiction of solar physics that we can only understand the equilibrium of a small and strong magnetic field element if there is a sunspot or pore present. Then we get an equilibrium of pressure inside and outside the magnetic element. But rather than a darkening, one in fact finds a brightening in these magnetic elements so long as the flux is not great enough to produce a sunspot. Spruit has attributed this to our seeing the bright hot walls of depressed invisible sunspots, but he has also shown that the curve of visibility of these bright elements would not follow the observed curve of facular visibility. There is an additional problem in that we observe a 30% brightening in a 1 arcsecond element. If the magnetic element only filled 1/10 of that area, it would have to be 3 times as bright as the photosphere, which would make it spectacular indeed. If it in fact matched the area supposed for 1000 Gauss fields, it would have to be 30 times brighter than the photosphere. This means that at the smallest scales there is a decoupling between the brightening in the upper photosphere and the magnetic field or else Stenflo is wrong and the fields are not 1000 Gauss. Whatever the truth is, we probably will get at it by making the highest resolution observations of faculae both in disk center and near the limb in a number of wavelengths. While you may think that .07 arcseconds is beneath the resolution of HRSO, I should point out that the resolution of a diffraction limited 1 meter telescope at 2000\AA is in fact .04 arcseconds, and there is no reason why the HRSO mirror could not be figured to deliver this resolution. Even if the mirror is only figured to the diffraction limit at 5000\AA the resolution at the shorter wavelengths will be always better. While I know that there is some cost involved to obtaining a mirror of better figure, the HRSO mirror is well within the state of the art and it would make sense to make a strong effort to provide the very best optical figuring which would make it capable of observation in this range. The mirror would have to be figured to λ by 50RMS at 6328\AA .

Impulsive Events

At one time HRSO was a quiet sun instrument and somebody told us we would not be allowed to take pictures of flares. Then it became a solar maximum instrument and we are going to look at flares. Now it is receding into the next sunspot minimum and we don't know what we will see. There are two extremely important observations of flares that can be made with the PFI: a spectrum of white light flares and the smallest element of flare kernels.

Spectrum of White Light Flares

White light or continuum flares present two extraordinarily difficult contradictions: first, they show a strong brightening in the blue and second, we don't know how the flare

energy gets down to the photosphere where we observe them in the continuum. With the PFI we should at least be able to shed light on the first. The continuum intensity of a white light flare sharply increases below 4000\AA . There is some evidence from the one weak flare observed by the LPSP rocket experiment that this brightening continues into the violet. Various explanations for the blue continuum have been advanced. One reasonable explanation is that a flare consists of a number of hot elements with spectrum peaking far in the blue; one example would be a $10,000$ degree black body with a peak emissivity at 2500\AA . With the PFI we hope to take rapid exposures on white light flares in a wide range of wavelengths down to 2100\AA . This should enable us to construct a black body curve for the emitting elements to see if they might follow this example. The problem is not so simple because the continuum brightness is occasionally 2 or 3 times the photosphere and this may be hard to explain by a simple increase in temperature. However there is no data below 3300\AA at present, and we should be able to pick up some sort of peak in the emissivity if it is a Planck function effect.

You may ask how I expect to observe so many white light flares in a 7-day flight. The answer is that the number of white light flares increases quite sharply with resolution. The LPSP observation showed that almost any little old flare will show continuum brightening at 2100\AA . It should be remembered that the greatest activity in the last cycle took place in 1982 and 1984 and the greatest activity in the preceding cycle in 1972 and 1974. If we are lucky, we too may see great activity on the launch of HRSO in 2004.

The Scale of Continuum Flare Kernels

We know from our original observations of the August 2, 1972 flare that kernels of the order of $1/2$ to 1 arcsecond are responsible for much of the continuum emission in impulsive white light flares. We hope the PFI will either resolve these and show they are no smaller or tell us how small they really are. These kernels of emission are closely correlated with X-ray bursts. While we hope that the HESP spacecraft is still active when HRSO flies, we can also use microwave observations to get an idea of the high energy aspects of these events. Determination of the scale of the flare footpoint kernels should give us another limit on the density and total energy in the hard electron flux producing these events.

Another target for the high resolution of the PFI will be growing sunspots. We have watched EFR's form from the ground and seen the small pores emerge from dark granule lanes. But the images are still too blurry to detect what actually happens. Further, we do not know what happens to the magnetic field. Coordination of continuum observations of forming sunspots with magnetograms from the CFS should yield important new results in this regard. Observation of the contrast of the new pores in a wide range of wavelengths will determine the change in temperature of same and show us how the cooling process proceeds as the pore forms.

High-Resolution Ground-Based Observations

Right now most of the proposed experiments for both groups do not take advantage of all we know or can learn about the small-scale structure of the photosphere. It is most

important that we learn as much as we can from the ground to direct our observations; we have only a little time for observing with HRSO and must use it wisely. The next film shows the evolution of the weak fields on the surface of the sun; Sara Martin will discuss later the details of magnetic interaction and reconnection among the magnetic elements. We have already found that the flux emerging in the intranetwork fields is two or three orders of magnitude above the flux in the ephemeral regions. I believe it crucial to push forward the high-resolution boundaries to better understand what we can get out of HRSO.

Some people have said to me we will be out of business in ground-based work after HRSO flies. That is nonsense. Our work will be strengthened because we will better understand what we are seeing, just as the Spacelab granulation data helps us understand and carry forward our granulation studies. Similarly, the idea that "rubber" mirrors and such will do the job of HRSO is also a fairy story because of the complexity of the atmospheric wave front distortion. Ask them for the high resolution pictures before you believe such tales.

PFI EXPERIMENTS

• ACTIVE REGIONS

A1. Development of Active Regions

A2. Emerging Flux Regions and Sunspot Creation and Growth

A3. Sunspot Structure and Dynamics

• SURFACE FLOWS

F1. Supergranular Flow

F2. Outflow in Sunspot Moats

• GRANULATION

G1. Temperature Structure and Evolution of Granule

G2. Search for Granulation Distortion by Large-scale Flows

G3. Height Variation of Granule Convective Overshoot

G4. Search for Latitude Dependence of Surface Convection

• HIGH SPEED PHENOMENA

H1. Flare Observation

H2. Eruptive Prominences

Figure 1.

PFI EXPERIMENTS

• MAGNETIC FINE STRUCTURE

M1. Interaction of Filigree and Granulation

M2. Diffusion of Magnetic Flux

M3. Photospheric Magnetic Structure at Neutral Lines

M4. Fine-Scale Magnetic Activity and Structure, Active Regions

M5. Fine-Scale Magnetic Activity and Structure, Quiet Regions

• ATMOSPHERIC STRUCTURE

S1. Limb darkening at extreme limb in all wavelengths

S2. Plage and facular brightness across the disk

Figure 2.

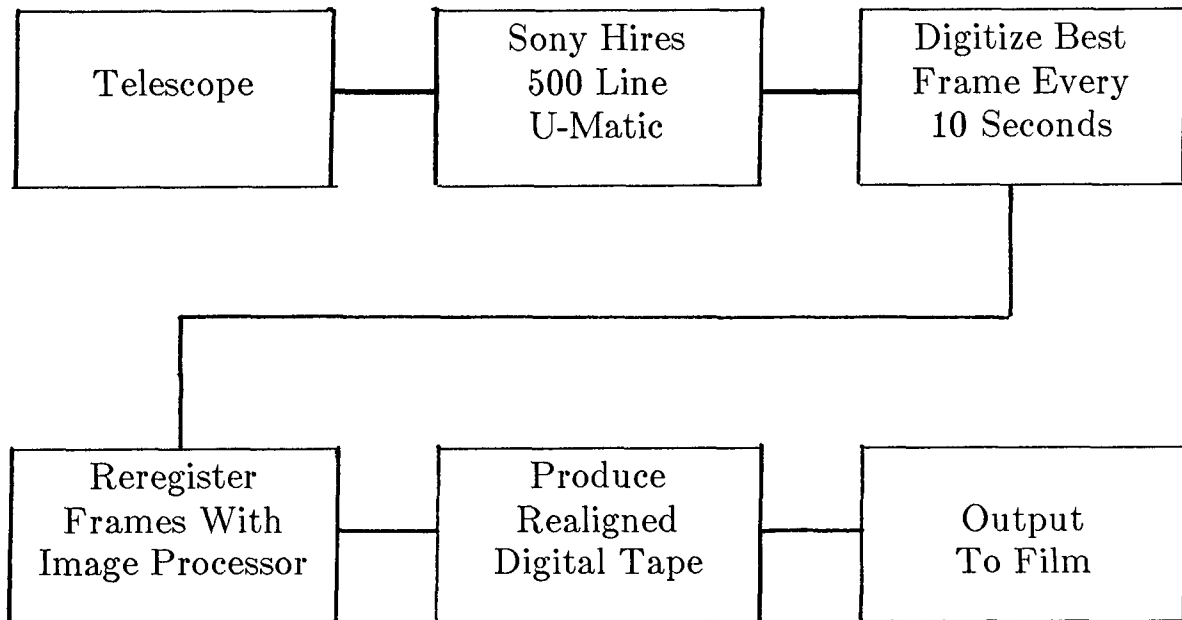
Mag Field Hierarchy

	Size	Life	Rate
AR's	10^{22} Mx	27 da.	10^{22} Mx/day
ER's	10^{20} Mx	1 da.	10^{23} Mx/day
Network	10^{18-20} Mx	1-3 da.	10^{23} Mx/day
Intra-Network	10^{16} Mx	1 hr.	10^{26} Mx/day

In Parameters

Flux: 10^{16} Mx Vel. 0.3-0.5 Km/sec. Lifetime 1-2 hrs.

Figure 3.



This process produces

1. Acceleration (visualize motions)
2. Continuity

Figure 4.